

# Efficient Quasiparticle Evacuation in Superconducting Devices

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We have studied the diffusion of excess quasiparticles in a current-biased superconductor strip in proximity to a metallic trap junction. In particular, we have measured accurately the superconductor temperature at a near-gap injection voltage. By analyzing our data quantitatively, we provide a full description of the spatial distribution of excess quasiparticles in the superconductor. We show that a metallic trap junction contributes significantly to the evacuation of excess quasiparticles.

In a normal metal - insulator - superconductor (N-I-S) junction, charge transport is mainly governed by quasiparticles [1]. The presence of the superconducting energy gap  $\Delta$  induces an energy selectivity of quasiparticles tunneling out of the normal metal [2, 3]. The quasiparticle tunnel current is thus accompanied by a heat transfer from the normal metal to the superconductor that is maximum at a voltage bias just below the superconducting gap ( $V \leq \Delta/e$ ). For a double junction geometry (S-I-N-I-S), electrons in the normal metal can typically cool from 300 mK down to about 100 mK [2, 4, 5]. However, in all experiments so far the electronic cooling is less efficient than expected [4, 5]. It has been proposed that this inefficiency is mostly linked to the injected quasiparticles accumulating near the tunnel junction area. This out-of-equilibrium electronic population, injected at an energy above the superconductor energy gap  $\Delta$ , relaxes by slow processes such as recombination and pair-breaking processes. The accumulation of quasiparticles is aggravated in sub-micron devices, where the relaxation processes are restricted by the physical dimensions of the device, leading to an enhanced density of quasiparticles close to the injection point. These quasiparticles can thereafter tunnel back into the normal metal [6], generating a parasitic power proportional to the bias current [7, 12]. The same phenomenon is relevant to other superconductor-based devices such as qubits [8], single electron transistors [9] and low temperature detectors [10].

In hybrid superconducting devices fabricated by multiple angle evaporation, a normal metal strip in tunnel contact with the superconducting electrode acts as a trap for excess near-gap quasiparticles, which removes them from the superconductor. This mechanism is usually not fully efficient due to the tunnel barrier between the normal metal and the superconductor [11]. A detailed theory of non-equilibrium phenomena in a superconductor in contact with normal metal traps has been developed [12]. However, a quantitative comparison between experiments and theoretical predictions is so far still missing.

In this Letter, we present an experimental investigation

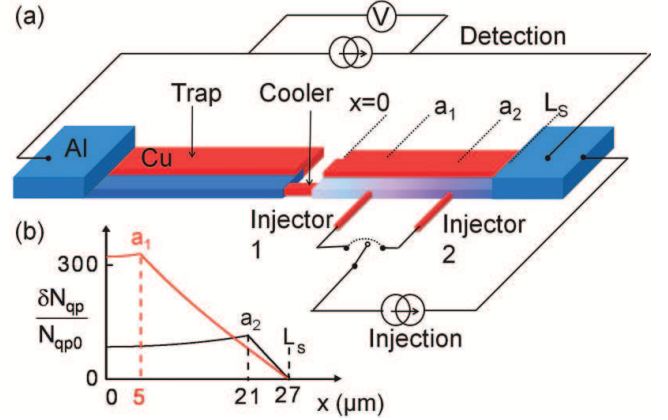


FIG. 1: (a) Schematic of the sample design with a trap junction on each S-strip of the superconducting microcooler. The curve shows the spatial profile of the excess quasiparticles  $\delta N_{qp}$  along the S-strip. The two injectors are located at  $a_1 = 5 \mu\text{m}$  or  $a_2 = 21 \mu\text{m}$ ; the detector (cooler junction island) is at  $x = 0 \mu\text{m}$  and the length of the S-strip is  $L_s = 27 \mu\text{m}$ . (b) Calculated spatial decay of excess quasiparticles density  $\delta N_{qp}$  along the S-strip. The two injectors are biased at  $eV/\Delta=4$ .

of the diffusion of out-of-equilibrium quasiparticles in a superconducting strip covered with a trap junction. A N-metal is used to inject quasiparticles in the S-strip. The local superconductor temperature is inferred from the heating of the central N-island of a S-I-N-I-S junction. We quantitatively compare our experimental data with a recently discussed theoretical model [7].

We have used a S-I-N-I-S cooler device with a trap geometry similar to the one studied in Ref. [13], see Fig. 1. These devices are fabricated using electron beam lithography, two-angle shadow evaporation and lift-off on a silicon substrate having 500 nm thick  $\text{SiO}_2$  on it. The central normal metal Cu electrode is  $0.3 \mu\text{m}$  wide,  $0.05 \mu\text{m}$  thick and  $4 \mu\text{m}$  long. The  $27 \mu\text{m}$  long symmetric S-strips of Al are then partially covered, through a tunnel barrier, by a Cu strip acting as a trap junction. At their extremity, the S-strips are connected to a contact pad act-

ing as a reservoir. In addition to the cooler island, we added two normal metal Cu tunnel injector junctions of area around  $0.09 \mu\text{m}^2$  on one S-strip. Injector 1 and 2 are at a distance of  $a = 5 \mu\text{m}$  and  $21 \mu\text{m}$  respectively from the central Cu island. The Al tunnel barrier is assumed to be identical in the cooler, probe and trap junctions, since they have similar specific tunnel resistance. The normal state resistance of the double-junction S-I-N-I-S cooler is  $1.9 \text{ k}\Omega$ . The normal state resistance of N-I-S injector junctions 1 and 2 are respectively  $2.5 \text{ k}\Omega$  and  $2.3 \text{ k}\Omega$ . The diffusion coefficient of the Al S-strip film was measured at  $4.2 \text{ K}$  to be  $30 \text{ cm}^2/\text{s}$ .

N-I-S tunnel junctions are known to enable controlled quasiparticle injection in a superconductor [14, 15, 21]. The tunnel current through a N-I-S junction is given by:

$$I(V) = \frac{1}{eR_N} \int_0^\infty n_S(E)[f_N(E - eV) - f_N(E + eV)]dE \quad (1)$$

where  $R_N$  is the normal state resistance,  $f_N$  is the electron energy distribution in the normal metal and  $n_S$  is the normalized density of states in the superconductor. In a superconducting wire undergoing quasiparticle injection, the superconductor gap  $\Delta(T_S)$  is suppressed locally. As this gap can be extracted from a N-I-S junction current-voltage characteristic, such a junction can be used for quasiparticles detection. Usually, an effective superconductor temperature  $T_S$  is inferred from the superconductor gap-temperature dependence. Fig. 2(a) displays the differential conductance  $dI/dV$  of a N-I-S probe junction (similar to an injector in Fig. 1(a)) located on a S-strip at different cooler bias voltages. At high injection, the gap suppression appears clearly, and enables a good determination of the superconductor effective temperature. This approach was used in numerous previous studies [14, 15, 21]. At lower injection with a voltage closer to the gap voltage, the tunnel characteristic becomes little sensitive to quasiparticle injection. For instance, in Fig. 2a the probe junction characteristic at  $1 \text{ mV}$  injection voltage almost overlaps the equilibrium characteristic (at  $0 \text{ mV}$ ). This limitation comes naturally from the saturation of the superconducting gap at low temperature  $T_S \ll T_C$ , where  $T_C$  is the superconductor critical temperature. So far, the insensitivity of the N-I-S junction characteristic at low injection bias has been a major roadblock in investigating the decay of quasiparticles injected at energies just above the gap [15, 21].

Instead of measuring directly the superconductor, a better detection sensitivity can be achieved by measuring the temperature of a small N-island connected to superconductor through a tunnel barrier [20]. In the absence of excess quasiparticles in the superconductor, the N-island is in thermal equilibrium with it. When the superconductor is under injection, some of the excess quasiparticles population will escape by tunneling (even at zero bias) from the superconductor to the central N-island. The in-

jected quasiparticles population will then reach a quasi-equilibrium in the N-island with a electronic temperature  $T_N$  different from the cryostat temperature  $T_{\text{bath}}$ .

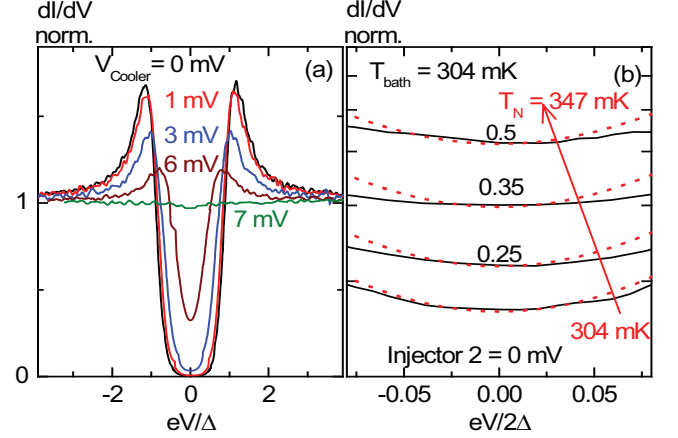


FIG. 2: (a) Probe junction differential conductance under different injection bias voltage from the S-I-N-I-S cooler junction. (b) Low bias cooler junction data (solid black lines) at different injector 2 voltage level compared to calculated isotherms (red dashed lines) as obtained from Eq. 1 with  $\Delta = 0.22 \text{ meV}$  at different  $T_N$ .

In this study, N-I-S junctions located on one S-strip of a S-I-N-I-S junction are used as quasiparticle injectors by current-biasing them. This leads to a spatial distribution of the excess quasiparticles density along the S-strip (see Fig 1 (b)). The central N-metal in the S-I-N-I-S cooler geometry is used as a detector for the quasiparticle density (at  $x = 0$ ) in the superconductor. In the N-island, the phase coherence time of about  $200 \text{ ps}$  (measured from a weak localization experiment in a wire from the same material) is much shorter than the mean escape time from the island estimated to about  $100 \text{ ns}$ . The N-island electronic population is then at quasi-equilibrium. Its temperature  $T_N$  can be extracted from the zero bias conductance level of the S-I-N-I-S junction [5]. Further, the superconductor temperature is inferred from the N-metal temperature by considering its heat balance. As demonstrated below, this scheme is highly sensitive down to about  $200 \text{ mK}$ , where the S-I-N-I-S junction I-V becomes dominated by the Andreev current [13].

Fig. 2(b) shows the differential conductance of the cooler junction (full black lines) at different injector-2 bias voltages along with isotherms (dotted red lines) calculated from Eq. 1. Fig. 3(a) displays the central N-metal temperature extracted from the zero-bias conductance as a function of injector bias voltage. As the injector bias increases above the bath temperature  $T_{\text{bath}}$ , the temperature  $T_N$  increases, indicating that more quasiparticles tunnel from the S-strip to the N-island.

In order to obtain the superconductor temperature  $T_S$  at the cooler edge ( $x = 0$ ), we need to consider the heat balance in the normal metal. The heat flow across a N-

I-S junction with different quasiparticle distribution on either side of the tunnel barrier is given by:

$$P_{heat}(T_N, T_S) = \frac{1}{e^2 R_N} \int_{-\infty}^{\infty} E n_S(E) [f_N(E) - f_S(E)] dE \quad (2)$$

where  $f_S$  is the energy distribution function in the superconductor at temperature  $T_S$ . It is compensated by electron-phonon coupling power  $P_{e-ph}$  so that  $P_{heat} + P_{e-ph} = 0$ . Here, we have used the usual expression for the electron-phonon coupling  $P_{e-ph} = \Sigma U (T_N^5 - T_{ph}^5)$ , where  $\Sigma = 2 \text{ nW} \cdot \mu\text{m}^{-3} \cdot \text{K}^{-5}$  in Cu is a material-dependent constant and  $U$  is the metal volume. For the normal metal phonons, the electron-phonon coupling power is compensated by the Kapitza power  $P_K(T_{ph}; T_{bath}) = K A (T_{bath}^4 - T_{ph}^4)$ , where  $K$  is an interface-dependent parameter and  $A$  the contact area. The inset of Fig. 3(a) displays the correspondence between the superconductor temperature  $T_S$  and the central N-metal temperature  $T_N$ . We took the fitted Kapitza coupling parameter value  $K \cdot A = 144 \text{ pW} \cdot \text{K}^{-4}$  found in Ref. [13] in a very similar sample. The grey area shows the calculated temperature  $T_S$  at different Kapitza coupling coefficient  $K$  ranging from  $120 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$  to infinity. The uncertainty in  $T_S$  due to uncertainty in  $K$  is negligible below 400 mK and at  $T_S$  at 600 mK it is only 15 mK.

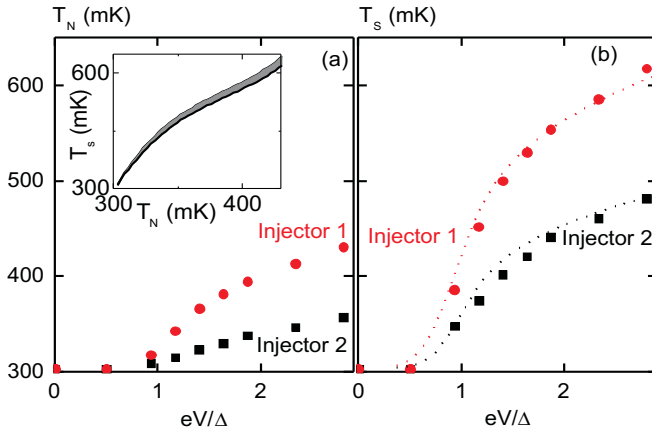


FIG. 3: (a) Central N-metal electronic temperature  $T_N$  dependence on the injector 2 bias voltage at the bath temperature of 304 mK. Error in  $T_N$  is smaller than the symbol size. Inset: calibration of the extracted superconductor temperature  $T_S$  to the measured normal metal temperature  $T_N$ . The grey area shows the uncertainty in  $T_S$  for different values of the Kapitza coupling coefficient. (b) Corresponding extracted S-metal temperature  $T_S$  at  $x = 0$ . Dotted lines are fits using  $D_{qp} = 35 \text{ cm}^2/\text{s}$ .

Fig. 3(b) and Fig. 4 show the extracted superconductor temperature  $T_S$  at the cooler edge ( $x = 0$ ) for different injection bias, in the two injectors at three different bath temperatures  $T_{bath} = 100 \text{ mK}$ ,  $304 \text{ mK}$  and  $500 \text{ mK}$  respectively. We have succeeded in obtaining

accurately the superconductor temperature for injection bias voltage close to the gap voltage. For a given injection bias in the two injectors, the temperature  $T_S$  of the detector at  $x = 0$  is higher for a closer injector. This confirms qualitatively the diffusion-based relaxation of hot quasiparticles in the superconductor.

In an out-of-equilibrium superconductor, the quasiparticle density  $N_{qp}$  and the phonon density of  $2\Delta$  energy  $N_{2\Delta}$  are coupled to each other by the well-known Rothwarf-Taylor (R-T) equations [16]. In a recent work [7], some of us have extended the R-T model to include the influence of the trap junction on the quasiparticle diffusion. We considered a superconducting strip covered by a second normal metal separated by a tunnel barrier, which is in practice equivalent to a device fabricated with a shadow evaporation technique [2]. The normalized excess spatial quasiparticle density  $z(x)$  in the S-strip is given by the solution of the differential equation:

$$D_{qp} \frac{d^2 z}{dx^2} = \frac{z}{\tau_0} + \frac{z + z^2/2}{\tau_{eff}}. \quad (3)$$

From this equation, one can find the quasiparticle decay length  $\lambda = \sqrt{D_{qp} \tau_{eff} / \alpha}$ , where  $\tau_{eff}$  is the material dependent effective recombination time and  $\alpha = 1 + \tau_{eff} / \tau_0$  ( $> 1$ ) is the enhancement ratio of the quasiparticle decay rate due to the presence of the trap junction. When the trapping effect is dominant, the quasiparticle decay length reduces to  $\sqrt{D_{qp} \tau_0}$ . The trap characteristic time  $\tau_0$  describes the rate of quasiparticles escaping to the N-metal trap. It is defined as  $\tau_0 = e^2 R_{NN} N(E_F) d_S$ , where  $R_{NN}$  is the specific resistance of the trap junction and  $d_S$  is the thickness of S. At equilibrium, the density of quasiparticles  $N_{qp0}$  in the superconductor at temperature  $T_S$  ( $< T_c$ ) decays exponentially:  $N_{qp0}(T_S) = N(E_F) \Delta (\pi k T_S / 2 \Delta)^{1/2} \exp[-\Delta / k T_S]$ , where  $N(E_F)$  is the density of states at the Fermi level.

In our experiment, the injectors are biased just above the gap voltage. Here, we assume that the injected quasiparticles relax fast (in comparison to other recombination processes) to the superconductor gap energy level and thus can be afterwards adequately described by the coupled R-T equations. To compare our experimental result with the theoretical model, we have extended the description shown in Ref. [7]. We solved Eq. 3 numerically with boundary conditions so as to include the injection:  $\frac{dz}{dx}|_+ - \frac{dz}{dx}|_- = \frac{I_{inj}}{\lambda}$  at  $x = a$ ; the detection:  $\frac{dz}{dx} = 0$  at  $x = 0$ ; and the finite length of the S-strip:  $z = 0$  at  $x = L_S$  into the model. The last boundary condition  $x = L_S$  provides an additional path for the excess quasiparticles to thermalize in addition to the N-trap. Further, the locally enhanced quasiparticle density  $N_{qp}(x)$  is described by an equilibrium quasiparticle density  $N_{qp0}$  such that  $N_{qp}(x = 0) = N_{qp0}(T = T_S)$  to obtain the theoretical superconductor temperature  $T_S$  [17].

In the fit procedure, we used the calculated values of  $\tau_{eff}$  and  $\tau_0$ . The calculated effective recombination time

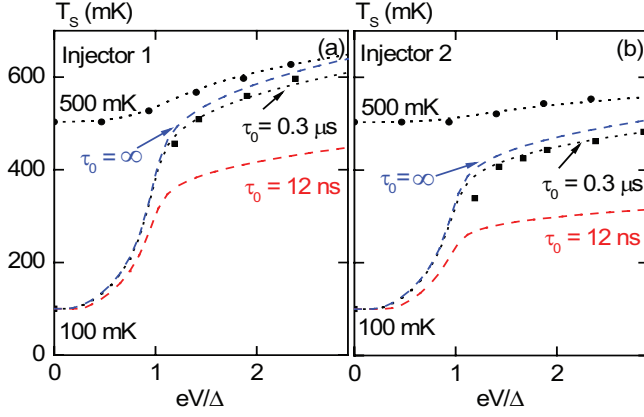


FIG. 4: Extracted superconductor temperature  $T_S$  as a function of injector bias voltage at a cryostat temperature of 100 mK (square dots) and 500 mK (circle dots). (a) and (b) correspond to an injection from injector 1 and 2 respectively. Dotted lines show the fits with the parameter  $D_{qp} = 35 \text{ cm}^2/\text{s}$ . Red and blue dashed lines are the calculated curve with the same  $D_{qp} = 35 \text{ cm}^2/\text{s}$  and for  $\tau_0 = 12 \text{ ns}$  and  $\infty$  respectively.

for Al is  $\tau_{eff} = 14 \mu\text{s}$ , [18] which is close to the experimental value in Ref. [19]. For our sample parameters, the calculated trap characteristic time  $\tau_0$  is equal to  $0.3 \mu\text{s}$ . The model has then only one free parameter, which is the quasiparticle diffusion coefficient  $D_{qp}$ . We obtain a quantitative agreement between the theoretical predictions for  $D_{qp} = 35 \text{ cm}^2/\text{s}$  and the experiment (dotted lines in Fig. 3(b) and Fig. 4) on the two injectors, for every injection voltage, and for a bath temperature of 100 mK to 500 mK. The fit-derived value of  $D_{qp}$  is comparable to the measured diffusion coefficient for Al at 4.2 K, and corresponds to  $\lambda = 30 \mu\text{m}$ .

This excellent agreement demonstrates that we quantitatively understand the diffusion of quasiparticles in the superconductor in proximity with the metallic trap junction. The quasiparticles relax mostly through two channels: N-metal trap (decay length  $\lambda$ ) and absorption in the reservoir (decay length  $L_S$ ). In our device, the decay length of both channels is around  $30 \mu\text{m}$ , thus they act with a similar efficiency. Fig. 4 red and blue dashed lines shows the calculated superconductor temperature  $T_S$  at  $T_{bath} = 100 \text{ mK}$  for a more transparent trap junction  $\tau_0 = 12 \text{ ns}$  and  $\infty$ , in parallel to the experiment and its fit. For  $\tau_0 = \infty$ , the excess quasiparticles relax at the reservoir  $x = L_S$ . For  $\tau_0 = 12 \text{ ns}$ , the decay length is  $\lambda = 6.5 \mu\text{m}$ , so that trapping then dominates the quasiparticles absorption. At such transparency the influence of proximity effect cannot be ignored [12].

In conclusion, we have studied experimentally the diffusion of quasiparticles injected in a superconductor with an energy close to the gap voltage  $\Delta$  in the presence of normal metal trap traps. Our study demonstrates that in such devices quasiparticle trapping competes with relaxation in the reservoir. This new knowledge is of

great importance in improving the geometry of the future cooling devices and other superconductor, based low-temperature devices.

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